CCI+ PHASE 1 – NEW ECVS
PERMAFROST

CCN1 & CCN2
ROCK GLACIER KINEMATICS AS NEW ASSOCIATED PARAMETER OF ECV PERMAFROST

D5 Climate Assessment Report

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EXECUTIVE SUMMARY

The European Space Agency (ESA) Climate Change Initiative (CCI) is a global monitoring program that aims to provide long-term satellite-based products to serve the climate modelling and climate data user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) that are elaborated during Phase 1 of CCI+ (2018-2021). For periglacial mountain environments, three options initiated within CCN1 and CCN2 addressed the need for additional regional cases aiming for more detailed characterization of mountain permafrost.

This document, the Climate Assessment Report (CAR), summarizes the added value of the Permafrost_cci products retrieved in periglacial mountain environments within CCN1 and CCN2. First, the CAR reviews the generated products, which comprise, according to the user requirements and algorithm development, (i) regional rock glaciers inventories (RGI), (ii) selected rock glacier kinematic time series (RGK), and (iii) a mountain permafrost distribution model (MPDM) in the Romanian Carpathians. Further on, the CAR provides an assessment of the products and other feedback from the research community, the regional permafrost modelers in mountain areas, remote sensing scientists, and field scientists working in mountain permafrost areas. Compared to the baseline project (with three iterations) only one algorithm iteration was made within CCN1 and CCN2. However, the CAR also lists expected improvements of the products for future use, such as the required development for operational monitoring of rock glacier kinematics and the possibility for an integrated monitoring approach for permafrost in marginal periglacial mountains regions in the Romanian Carpathians. Finally, publications and outreach activities relevant to dissemination of Permafrost_cci activities are listed.

Within the framework of CCN2, guidelines for inventorying rock glaciers based on kinematics have been developed and applied for the compilation of remote sensing based inventories in several regions worldwide. This demonstrates that the definition and application of common rules is feasible, despite various environmental settings, problems related to the calculation of annual average values or the definition of homogenous units, and the fact that mapping rock glaciers requires geomorphological expertise and intensive manual effort. Lessons learned from this work will be extremely valuable to refine the guidelines and open the way to apply them in many more areas, as well as to provide excellent data for training, validation and testing of artificial intelligence algorithms for automatic detection and delineation of rock glaciers from satellite imagery.

The rock glacier kinematic time series produced within the framework of CCN1 and CCN2 demonstrate that the objective to associate harmonized rock glacier kinematic time series to the ECV Permafrost with remote sensing data is feasible. The large advantage of remote sensing time series of seasonal variations of rock glacier velocities is that they can be derived over large areas worldwide in a largely automated way. Being able to use the high temporal resolution between satellite images (SAR data in particular) allows detailed rock glacier deformation time series to be obtained, which enables increased seasonal resolution and thus an improved understanding of potential causes for changes in dynamics.

1 INTRODUCTION

1.1 Purpose of the document

The products required within CCN1 and CCN2 of the ESA CCI project for mountain permafrost regions include (i) regional kinematics-based rock glaciers inventories (RGI), (ii) kinematic time series on selected rock glaciers (RGK), and (iii) a mountain permafrost distribution model (MPDM) in the Carpathians. This document provides the Climate Assessment Report (CAR) of CCN1 and CCN2 with the ultimate purpose to document the added value of the data set generated in terms of improvement over existing products.

1.2 Structure of the document

The first part of this document provides information on related documents and general permafrost related information. Section 2 includes information on the developed products. Section 3 covers the user feedback. Section 4 reviews the algorithm selection and initial user requirements and discuss future potential work development related to CCN1 and CCN2 outcomes. Section 5 provides an overview of publications and outreach.

1.3 Applicable documents

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[RD-2] A. Bartsch, S. Westermann, T. Strozzi, A. Wiesmann, C. Kroisleitner: ESA CCI+ Permafrost Product Specifications Document (PSD), v2.0 30 November 2019

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[RD-6] S. Westermann, A. Bartsch, B. A. Heim, T. Strozzi: ESA CCI+ Permafrost End-to-End ECV Uncertainty Budget (E3UB), v2.0 30 November 2019

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[RD-32] A. Bertone, C. Barboux, R. Delaloye, L. Rouyet, T.R. Lauknes, A. Kääb, H. H. Christiansen, A. Onaca, F. Sirbu, V. Poncos, T. Strozzi, R. Caduff and A. Bartsch, 2020: ESA CCI+ Permafrost. CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.3 Product User Guide (PUG), v1.0 23 December 2020

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 5.1.

1.6 Acronyms

A list of acronyms is provided in section 5.2.

1.7 Glossary

A comprehensive glossary of terms relevant for the parameters addressed in Permafrost_cci is available as part of the Product Specifications Documents of the baseline project [RD-2] and of CCN 1 [RD-22].

2 PRODUCTS GENERATED BY PERMAFROST_CCI

The Permafrost_cci baseline project is focused on ground temperature and derived products such as the active layer thickness and permafrost area maps. This implies the production of consistent, stable and error-controlled products, covering the period with available EO data from 1997 to date. Algorithms have been identified which can provide these parameters ingesting a set of global satellite data products (Land Surface Temperature LST, Snow Water Equivalent SWE, and land cover) in a permafrost model scheme that computes the ground thermal regime [RD-5]. Annual averages of ground temperature and annual maxima of thaw depth (active layer thickness) were provided at 1 km spatial resolution during Years 1&2 of Permafrost_cci. The data sets were created from the analysis of lower level data, resulting in gridded, gap-free products.

In periglacial mountain environments, the permafrost occurrence is patchy but increases in percentage area coverage with elevation. The preservation of permafrost is controlled by site-specific conditions. Three options of Permafrost_cci initiated within CCN1 and CCN2 address the need for additional regional cases in cooperation with dedicated users in characterizing mountain permafrost as local indicator for climate change and direct impact on the society in mountainous areas.

CCN1 started in October 2018 and was led by a Romanian team focusing on case studies in the Carpathians. Specific user requirements for the case study that include mountain permafrost in Southern Carpathians for ground temperature and active layer thickness have been compiled in [RD-16]. They demand a regional geographical coverage (regional permafrost extent Southern Carpathians, 14,000 km²), high temporal resolution (monthly data), high spatial resolution (target resolution 0.1 km) including representation of sub-grid variability, and long temporal coverage (one to several decades back in time). These requirements go considerably beyond the state-of-the-art in remote permafrost ECV assessment, based on published studies and recently demonstrated progress [RD-5]. For the specific mountain permafrost sites located in Southern Carpathians, other permafrost products, primarily derived from satellite measurements, were thus defined and specified in [RD-16], i.e. (i) permafrost distribution model, (ii) trends in velocity of selected rock glaciers, and (iii) rock glacier inventory. Algorithms to create permafrost distribution models and to derive trends in velocity of selected rock glaciers are part of the processing system implemented in CCN1 [RD-17]. Algorithms to compile rock glacier inventories, on the other hand, were not considered, because the aim of the work specified for CCN 1 was only to enrich an existing rock glacier inventory consisting of 306 landforms (Onaca et al., 2017) with information about the activity status of rock glaciers and the permafrost occurrence.

CCN2 started in September 2019 and consists of two options led by Swiss and Norwegian teams focusing on the investigation and definition of a new associated ECV Permafrost product related to rock glacier kinematics. Early 2020, Rock Glacier Kinematics (RGK) has been proposed as a new product to the ECV Permafrost for the next GCOS Implementation Plan (IP). It would consist of a global dataset of surface velocity time series measured/computed on single rock glacier units. As the velocity tends to increase when the permafrost temperature is rising, a proper rock glacier kinematics monitoring network, adapted to climate research needs, builds up a unique validation dataset for climate models of mountain regions, where direct permafrost (thermal state) measurements are very scarce or even lacking totally. CCN2 is working closely with the IPA (International Permafrost Association) Action Group Rock glacier inventories and kinematics, gathering about 150 members [AD-10 to AD-13]. Following the recommendations of this IPA Action Group, the overall goal of CCN2 is achieved through the development of two products: (i) regional kinematics-based rock glacier inventories and (ii) kinematic time series of selected rock glacier.

In summary, the products required within CCN1 & CCN2 of the ESA CCI project for mountain permafrost regions include (i) regional rock glaciers inventories (RGI), (ii) selected rock glacier kinematic time series (RGK), and (iii) a mountain permafrost distribution model (MPDM) in the Romanian Carpathians.

Kinematics-based Rock Glacier Inventories (RGI) were generated by different CCI groups and external providers. Entirely new kinematics-based rock glacier inventories or updates / upgrades of existing inventories have been generated according to the standards defined by the IPA Action Group on rock glacier inventories and kinematics [RD-31 and RD-32] in different climatic regions:

- European Alpine sites: Western Alps (Switzerland), Ultental (Italy), Vanoise Massif (France);
- European subarctic/arctic sites: Troms, Finnmark (Northern Norway), Nordenskiöld Land (Svalbard);
- Extra-European sites: Disko Island (Greenland), Tien Shan (Kazakhstan-Kyrgyzstan), Brookes Range (Alaska), Central Andes (Argentina), Southern Alps (New Zeeland).

Kinematic time series (RGK) on selected rock glaciers in the Swiss Alps, Norway, Svalbard, Disko Island (Greenland) and Romanian Carpathians were produced mainly based on SAR data. Trends in rock glacier velocity were computed from ALOS-2 PALSAR-2 and Sentinel-1 SAR interferometry.

The mountain permafrost distribution model (MPDM) product from CCN1 shows that permafrost distribution in the Southern Carpathians is patchy, being able to exist only under certain topographical conditions. The total permafrost area has an extent of, most likely, 3 km^2 (possibly between 0.1 km^2 to 7.74 km^2).

3 ASSESSMENT OF PRODUCTS AND OTHER FEEDBACK

3.1 Mountain Permafrost Distribution Model (MPDM) at regional scale in the Romanian Carpathians

3.1.1 Introduction and rationale

The assessment of the Mountain Permafrost Distribution Model (MPDM) at regional scale in the Romanian Carpathians has been performed by Adrian Cristian Ardelean from the National Museum of Banat. He has previous experience in permafrost modelling and vast geomorphological knowledge about the alpine area in the Southern Carpathians.

While permafrost research in some of the major mountain chains around the world (e.g. the Alps, the Andes, the Scandinavian Alps, the Pyrenees etc.) is developed and globally visible, there is a paucity of studies concerning permafrost in other areas. In the particular case of the Romanian Carpathians, scientific evidence concerning the permafrost is sparse. Despite several recent findings, the spatial distribution of permafrost in the Romanian Carpathians is still poorly known. Thus far, previous scientific research has focused on documenting new areas of permafrost in the Southern Carpathians, but no analyses of the permafrost distribution at a regional scale have yet been performed. Based on the reported scientific results, permafrost is expected to occur above 2000 m on the north-facing slopes of the highest mountain ranges in the Southern Carpathians and its occurrence is restricted only to openwork structures characterized by a high porosity (Onaca et al., 2015). In most of the cases, the occurrence of permanently frozen materials is associated with permafrost creep landforms (e.g., rock glaciers) (Popescu et al., 2017).

3.1.2 Assessment of the MPDM at regional scale using random forest algorithm

The permafrost map produced by the permafrost distribution model [RD-19] is the first region-wide permafrost map in the Southern Carpathians. It provides insights into the probability of permafrost occurrence in previously unstudied mountain ranges (e.g. Bucegi, Șureanu). Particularly it predicts a high permafrost occurrence probability in Bucegi, a mountain range with a relatively vast alpine area but where no permafrost investigations have been performed. The parameters of the model (i.e. spatial resolution, accuracy) are above the required threshold for a region wide model and are sufficient for providing a general overview about permafrost context in the study area.

The model does not contain a temporal component and thus cannot track the evolution of permafrost and it cannot predict its evolution into the future. However, the model is developed as an automated script, that can be run multiple times. It means that the results can easily be updated if there is a change in the input data.

The areas that show a high permafrost probability are somehow correlated with rock glacier distribution and are usually located in glacial cirques. On the well-studied Pietrele, Judele Valea Rea and Galeșul rock glaciers, both the areas with a high and low probability of permafrost occurrence are in accordance with previous thermal and geophysical studies.

3.2 Trends in rock glaciers velocity in the Romanian Carpathians

3.2.1 Introduction and rationale

The assessment of the trends in rock glaciers velocity in the Romanian Carpathians has been performed by Adrian Cristian Ardelean from the National Museum of Banat. He has previous experience in permafrost modelling and vast geomorphological knowledge about the alpine area in the Southern Carpathians.

Urdea (1998) compiled the first rock glacier inventory in the highest mountains of Romanian Carpathians. This incomplete inventory consisted of analogue drawings of rock glacier contours on topographic maps at scale 1:25 000 for several mountain ranges (Retezat, Făgăraș and the western part of Parâng Mountains). More recently, using high quality air-orthophoto data, high resolution topography data and a complementary field survey, Onaca et al. (2017) realized the first polygon-based digitalized inventory of rock glaciers for the Southern Carpathians. The first measurements of rock glaciers dynamics were initiated in the Retezat Mountains, using ground-based geodetic surveys by Vespremeanu-Stroe et al. (2012). A recent approach (Necsoiu et al. 2016) based on a combination of optical and radar remote sensing techniques (coherence analysis, correlation analysis and multitemporal InSAR techniques) allowed the evaluation of the displacement rates of several rock glaciers from the central part of the Retezat Mountains. Because the deforming frozen layer within the investigated rock glaciers appears to be very thin, the velocity of these landforms was very low compared with other active rock glaciers located in other parts of the world. Displacement rates of few centimetres/year were recorded in case of Pietrele rock glacier in the Retezat Mountains.

3.2.2 Assessment of trends in rock glaciers velocity from ALOS-2 PALSAR-2 and Sentinel-1 SAR interferometry

The rock glacier velocity assessment covers the area of the Southern Carpathian and improves the existing inventory compiled by Onaca et al. (2017) by adding information about rock glacier (RG) dynamics. Rock glaciers in general do not have a constant velocity throughout the whole year; they experience sudden accelerations/decelerations in relation with air/ground temperature variations. The 30-days temporal resolution of the results is sufficient to capture this movements. Although considering the slow moving rate of the rock glaciers in the Southern Carpathians, yearly rates of velocities are sufficient and easier to interpret.

The velocity rates are consistent with previous studies regarding RG activity and thermal ground regime (Onaca et al. 2013, Ardelean et al. 2015, Popescu et al. 2016). It shows that detectable movement only occurs for a small number of rock glaciers and the majority of them are only partially active. Again, this is in accordance with previously published studies (Onaca et al. 2015, Necsoiu et al. 2016, Onaca et al. 2017).

3.3. Cross validation between MPDM and RG dynamics in the Romanian Carpathians

The two outputs of CCN1, the permafrost extension model and the RG dynamics, are compared for the central area of Retezat Mountains. Because permafrost occurrence is in direct relation with rock glacier dynamics, the two outputs can be used for cross validation.

The modelled permafrost distribution map covers the entire region, inside and outside of rock glaciers. While in the Southern Carpathians permafrost can be found on different geomorphological features (e.g. scree slopes, rock streams), rock glaciers are the main landforms associated with permafrost occurrence. In the selected area, for the rock glaciers including modelled permafrost occurrence, there is a good overlap with the areas found to have movement by the Sentinel-1 derived velocities maps. This can be observed in Figure 1 for the SE part of Galeșul RG (1), Valea Rea1 (2) and Valea Rea2 (3) rock glaciers and the southern part of Valea Rea3 RG (4). For the rock glaciers that were modeled to be permafrost-free, no significant movement has been observed.

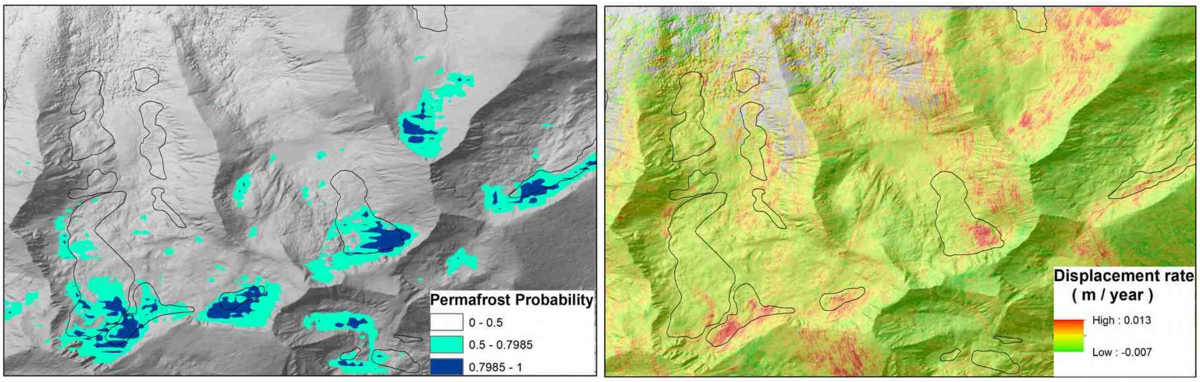

Figure 1. Comparison between the modelled permafrost distribution map (left) and the velocities map derived from Sentinel-1 using the InSAR stacking method (right) for four rock glaciers: 1 - Galeșu, 2 - Valea Rea, 3 - Valea Rea2, 4 - Valea Rea3.

3.4 Comments by Prof. Reynald Delaloye, University of Fribourg, Switzerland, chair of the IPA Action Group Rock glacier inventories and kinematics

3.4.1 Regional Kinematics-based Rock Glaciers Inventories

In a recent paper, Jones et al. (2019) estimated that more than 73'000 rock glaciers have been already once inventoried on the globe. The number of non-inventoried rock glaciers is unknown but certainly much larger. All so far existing regional inventories having been established for diverse motivations, being based on different methodologies and being of different ages, they are extremely heterogeneous in their form, content and reliability, what makes their assemblage and coherent exploitation an almost unfeasible task. The IPA Action Group Rock glacier inventories and kinematics was launched in 2018 with, among others, the objective of finding a consensus in the scientific community of concern to establish standard guidelines for inventorying rock glaciers and including information on their activity rate. The *Baseline concepts for inventorying rock glaciers* were released in 2020 as the first ever document coordinating methodologies for inventorying rock glaciers globally. It defines in particular the complementary geomorphological and kinematic approaches. Within the framework of CCN2 guidelines for inventorying rock glaciers on kinematics base have been developed by the two involved teams and the external partners. It represents a very important contribution for the works of the IPA Action Group.

The 11 resulting regional kinematics-based inventories delivered by CCN2 are representing the first ever internationally coordinated work of inventorying rock glaciers applying common rules, moreover in regions as diverse as the Central Andes, the northern Alaska, Greenland, the European Alps and sub-arctic region, the Central Asia and the Southern Alps in New Zealand. They demonstrate that the definition and application of common rules, despite very various environmental settings, is feasible. Not all aspects of the inventories are perfect and some improvements of both the guidelines and the inventories could be undertaken. But the lesson learned from this work will be extremely valuable to refine the guidelines and to open the way to apply them widely in many more areas.

3.4.2 Rock glacier kinematic time series (RGK)

The second objective of the IPA Action Group on rock glacier inventories and kinematics is to associate harmonized rock glacier kinematic time series to the ECV Permafrost and to promote the use of remote sensing data (SAR data in particular) to provide the necessary data worldwide. The first time-series produced within the framework of CCN1 and CCN2 demonstrate that such an objective is realistic. These time-series have been computed on several rock glaciers in regions as various as the Central Andes, Greenland, the European Alps, the sub-Artic regions of Norway and the Carpathians. The seasonal (intra-annual) behaviour of rock glaciers is diverse, but seasonally recurrent over time according to terrestrial measurements already performed on some accessible sites, in particular in the European Alps (e.g. Staub et al. 2016). The time-series provided by CCN1 and CCN2 are in line with these observations. However, considering the difficulties in properly monitoring the rock glacier movement in a continuous way all the year along terrestrially or remotely, participants to the IPA Action Group Workshop II (supported by CCN2) agree to focus the development of RGK on annual time-series exclusively. It means that the annual monitoring period could be restricted for instance to the seasonally snow-free period, but must be recurrent from year to year. The time-series provided by

CCN1 and CCN2 are fulfilling this requirement and show that the exploitation of such types of data in the frame of the expected future ECV RGK product is very promising.

3.5 Comments by Prof. Hanne H. Christiansen, field geomorphologist working with permafrost landforms in the Arctic and permafrost ECVs, based at The University Centre in Svalbard, UNIS, Norway

Assessment of the regional kinematics-based rock glaciers inventories (RGI), and the kinematic time series (RGK) on selected rock glaciers obtained within the CCI+ ESA project – with special focus on the Arctic areas

The key research objective of the CCI+ ESA project is to determine if another permafrost ECV – surface deformation – can be developed, to focus also on mountain permafrost dynamics more clearly in overall climatic observations of permafrost. These regions have hitherto typically not been well represented when studying the permafrost ECV distribution. This is as expected, as observations of the permafrost thermal state and in particular the active layer thickness using the standard methods are clearly much more challenging logistically in remote high relief cold climatic areas than in lowlands. Adding surface deformation to the existing permafrost ECVs will mark a new era of not just recording basic geophysical conditions as the exiting permafrost ECVS but starting to differentiate the understanding of how permafrost respond to climatic changes as different landforms can respond differently. Rock glaciers are one of few landforms that are solely dependent on permafrost, and therefore establishing its dynamics as an ECV is an important first step towards a more detailed understanding of how permafrost landscapes can respond to climatic changes.

The CCI+ project has carried out remote sensing based regional mapping of rock glaciers in several alpine and Arctic regions and compared this with ground-based measurements in the same areas. Also, extensive complete geomorphological mapping has been carried out in some of the study regions if no preliminary complete mapping of the extent of rock glaciers existed. In general, the results verify that the InSAR methods works with high consistency between the clearly creeping areas identified by InSAR and independently mapped rock glacier extents for all the Arctic areas.

The increased availability now exiting for satellite SAR images, enables interferometry to be used on a regular basis for mountain areas with down to 6 days between measurements in Europe and Greenland, and 12 days for other mountain areas. Clearly a remote sensing overview of deformation rates as the regional studies performed contains, provide an overview that no ground-based fieldwork will ever be able to obtain, and which is very useful. Being able to use the high time resolution between SAR images allows detailed rock glacier deformation timeseries to be obtained, which enables increased seasonal resolution and thus increased understanding about meteorologically caused seasonal changes in dynamics. This represents an important step forward in directly being able to observe and understand how changes in e.g., snow cover and/or its timing can affect rock glacier dynamics and thus indirectly permafrost.

To obtain the best and most precise observations of rock glacier dynamics for use as a permafrost ECV, it seems based on the presented results, that first a combination of a regional scale InSAR overview identifying deformation areas should be combined with independent existing or new detailed geomorphological mapping of creeping landforms allowing for identification of rock glaciers. Secondly, InSAR timeseries of the identified rock glaciers deformation rates should be verified by ground-based detailed measurements, to eliminate uncertainties and obtain the most detailed data. Then with time, as potentially the time intervals between SAR image acquisition becomes even shorter, and InSAR processing becomes automatized through the use of AI and machine learning to at least some degree, an important remote sensing and thus much more sustainable method has been developed allowing for detailed observations of rock glacier dynamics. This will be very important when aiming to understand the consequences of how climatic changes can affect permafrost mountain landscapes.

3.6 Comments by Prof. Andreas Kääb, University of Oslo, Norway

Comparison between InSAR-derived kinematic rock glacier inventories and terrestrial and photogrammetric measurements [RD-30] confirm the high reliability of the InSAR-based inventories. They give thus a largely complete overview of slope movements in cold mountains. This opens up new possibilities for the understanding and numerical modelling of cold-mountain landscape dynamics, which had so far to be based on detailed measurements on only a few landforms, if at all. For instance, the decreasing sediment transport through shrinking glaciers compared to the increasing sediment transport associated with accelerating rock glaciers suggest an increase in relative importance of periglacial processes over glacial ones, at least for some cold mountain ranges. This suggestion is in line with the higher thermal inertia of mountain permafrost compared to surface ice – an effect that also suggest increasing importance of periglacial environments under atmospheric warming. Implications of such expected changes include a wide range of scientific and applied disciplines; landscape dynamics (e.g. sediment production and transport); assessment of natural hazards (e.g. increasing debris flows from rock glaciers, or rock glacier instabilities); water resources (e.g. change in ice content of rock glaciers). The robust rock glacier kinematic inventories enable for the first time regional assessment of above topics based on regional measurements, and should thus be extended to larger areas and more regions. The harmonisation of methods and inventories as achieved within Permafrost_cci and the IPA Action Group on rock glacier inventories and kinematics is thereby the key to wider application and sound results from the inventory data.

Rock glacier kinematic time series shed light on the physics of rock glacier creep and its response to climate change. Variations of rock glacier creep happen on different temporal scales, whereas the decadal, interannual and seasonal ones seem currently of most interest. Decadal-scale speed changes should reflect the impact of climatic changes, interannual variations the influence of weather, and seasonal variations the sensitivity of individual rock glaciers to (change in) boundary conditions. The different significances of these temporal scales overlap with the capabilities from different remote sensing methods. As shown now within Permafrost_cci, recent advances in InSAR enable measurement of seasonal speed time series (mainly over the snow-free period), whereas photogrammetry derives average annual speeds over several years. Both measurements combined make it possible to measure rock glacier speeds at all three temporal scales listed above. For instance, photogrammetry is not able to provide seasonal speed variations, InSAR is. InSAR provides the understanding of how far photogrammetric measurements could be influenced by seasonal variability in speed, but is not strictly able to measure average annual velocities due to phase coherence loss over times scales larger than a few months for fast rock glaciers, and because measurements are complicated during snow-cover periods. Airphotos for photogrammetric measurements are potentially available far more back in time than satellite SAR data. From that it becomes clear that the remote sensing methods applied in Permafrost_cci option CCN2, InSAR and photogrammetry, are highly complementary and can hardly replace each other.

The large advantage of InSAR series of seasonal variations of rock glacier speed is, though, that satellite InSAR can be applied over large areas or worldwide in a largely automated way, not least due to the operational character of the Sentinel-1 mission. The proposed methodology for seasonal time series turns out very well feasible and promises a large step forward in global monitoring of rock glacier movement. The success of the method opens up a completely new field for the application of SAR (i.e. worldwide rock glacier speed monitoring). The examples elaborated in Permafrost_cci exhibit a large variation of seasonal and interannual rock glacier velocity variations. The examples given cover already the full range of high to low overall velocities, large and small velocity variations, and increasing and stable interannual evolution of velocities. Some rock glaciers seem to have large velocities throughout much of the year, some seem to become almost inactive over winter. These all are novel findings that will certainly much promote understanding of rock glacier creep and its response to climate change.

3.7 Comments by Prof. Lin Liu, The Chinese University of Hong Kong

Rock glaciers are debris-ice-mixture landforms widely distributed in the mountainous periglacial realm worldwide. Actively moving rock glaciers serve as important visible indicators for alpine permafrost. Rock glacier inventories provide baseline knowledge about permafrost extent and are essential for long-term monitoring and assessing climatic impacts on the periglacial environment. Moreover, rock glaciers contain massive amounts of ground ice and contribute significantly to hydrological systems in many catchments. A comprehensive inventory of rock glaciers lays the foundation for estimating the potential water storage and evaluating their future roles in maintaining water supplies.

The methodology used to inventory rock glaciers from satellite InSAR and optical images, initially pioneered and continuously improved by Drs. Reynald Delaloye, Tazio Strozzi, Andreas Kääb, and other core members of the rock glacier team within the ESA CCI+ Permafrost project (permafrost_cci in short), has matured and become the routine standard for carrying out inventorying, delineating boundaries, mapping surface velocities, and classifying levels of activities based on surface velocities. Still, mapping rock glaciers requires geomorphological expertise and intensive manual efforts. Moreover, different and even contentious opinions of identifying rock glaciers exist due to the complexity of the landforms. To promote the emergence of a global rock glacier inventory, the International Permafrost Association (IPA) Action Group on rock glaciers was proposed and has been led by Dr. Reynald Delaloye since 2018; most of the ESA CCI+ Permafrost team members and myself have been actively involved. By specifying the definition, essential attributes, and inventorying strategies, the IPA document serves as a practical manual for mapping rock glaciers in a standardized way. To my knowledge, the new rock glacier inventories developed by permafrost_cci are among the first that followed the recommendations and guidelines developed by the IPA action group. Therefore, the permafrost_cci rock glacier inventories, produced by more than 12 researchers from 9 institutes, covering 6 major mountain ranges over 5 continents, are remarkably consistent. The permafrost_cci rock glacier project, therefore, makes significant contributions towards building a global-scale, high-quality, standardized rock glacier inventory and will inspire and stimulate the broad international community to collaborate with the permafrost_cci in such endeavor.

My research group is awed and thrilled by such great efforts made by the permafrost_cci, and eager to build close synergy with the rock glacier team in two directions. First, at the basic level, we will take the examples set by permafrost_cci and strictly follow the IPA inventorying guidelines to produce rock glacier inventories over major mountain ranges in western China, especially on the Qinghai-Tibet Plateau. Compared with the European counterparts, rock glaciers over the vast western China remain poorly mapped. Since the same method and guidelines will be adopted, our rock glacier inventories will be readily integrated into the permafrost_cci products. Second, the permafrost_cci inventories provide excellent data for training, validating, and testing artificial intelligence algorithms for automatedly detecting and delineating rock glaciers from satellite imagery. The applications of deep learning for cryospheric and geomorphological studies are still in an early development stage and not yet ready for routine operations. One of the major bottlenecks is the lack of label data that can be directly used to train deep learning networks. The permafrost_cci inventories will be easily transformed as label data for the deep-learning-based semantic segmentation methods our research group has been developing.

3.8 Comments by Dr. Andreas Kellerer-Pirklbauer, University of Graz, Austria, national representative at the IPA for Austria; geomorphologist working with permafrost and periglacial landforms

My brief assessment on the mountain ESA CCI Permafrost products in CCN1 & CCN2is based on two reports which were available to me (Bertone et al. 2020, 2021). As outlined in these documents, the products required within CCN1 and CCN2 include (a) regional kinematics-based rock glaciers inventories, (b) rock glacier kinematic time series on selected rock glaciers, and (c) a mountain permafrost distribution model in the Romanian Carpathians. In detail, CCN1 dealt with (a), (b) and (c) focussing spatially in all three topics on the Romanian Carpathians. In contrast, CCN2 aimed at (a) and (b) but with globally distributed study sites. Both reports are interesting to read and report novel and promising results. From an editorial point of view, however, it is worth to mention that both reports would benefit from an editorial modification in terms of cartographical quality alignment (e.g., partly incomplete or missing map keys, wide range of cartographic styles, missing scales or north arrows, some non-English map keys, overview maps for orientation, coordinates), improvement of some graphics (e.g., partly missing captions for abscissa and ordinate axis), homogenisation of table styles, terminology alignment (GPS, DGPS, RTK-GPS, GNSS), or typo corrections.

3.8.1 Regional kinematics-based rock glaciers inventories

Within the framework of a workshop held in Switzerland in February 2020, various projects partners applied independent from each other their jointly and previously defined guidelines for kinematics-based rock glaciers inventorying using several wrapped interferograms covering two regions in the Western Swiss Alps. Such an inter-comparison exercise has shown to be a very useful approach to quantify to some extent the naturally given subjectivity in landform mapping as shown for rock glacier mapping and activity classification in one valley in Austria by Brardinoni et al. (2019) using optical EO data. Results of the inter-comparison exercise were used to refine the guidelines. These refined guidelines were subsequently applied to analyse interferograms (Sentinel-1, ALOS-1 PALSAR-1, ALOS-2 PALSAR-2) to compile new or update existing rock glacier inventories in the Northern (Swiss Alps, French Alps, Italian Alps, mainland Norway, Svalbard, Argentinian Andes, Tien Shan, Alaska, and Greenland) and Southern (New Zealand) Hemisphere. Validation (or "first step assessment") of the InSAR measurements at the study sites was achieved by GNSS or other remote sensing data (e.g., high-resolution optical satellite data). For two areas (Swiss Alps, Norway) the authors also present results of a second step consolidation phase which basically means that the interpretation of the dataset was accomplished by more than one operator aiming to improve the reliability of the inventory. In conclusion, the InSAR velocity data seem to be in good agreement with velocity data derived from other methods. However, a main first problem is the calculation of annual average values of rock glacier creep based on InSAR data which can only be used reliably during the snow-free period. The agreement between InSAR measurements with summer GNSS velocities is very good, but the conversion into annual kinematic pattern – which is the focus for rock glacier kinematic quantification - is a severe problem and the source for uncertainties. This circumstance is related to the seasonal but also uneven temporal variability of rock glacier movement typical for many rock glaciers. A second problem, as it was revealed in the "consolidation phase" for the Swiss rock glaciers, is the sound definition of homogenous units – in terms of velocity classes but also in terms of geomorphic characteristics – of a rock glacier. Discrepancies were detected in the identification of rock glacier units also related to lacking universal definitions and standards which are needed for a sound analysis. Third, the authors pointed out that the faster the movement, the greater the reliability of the classification which implies on the other hand that slower rock glaciers are more difficult to classify "correctly" with InSAR data. Fourth, the authors point out that a clear movement signal on a wider time span is necessary to quantify the displacement of a landform rather than noise in the data. In summary, important progress was made in CCN1 and CCN2 regarding the regional kinematics-based rock glaciers inventories. However, further research work – in both remote-sensing and field work-based approaches – is needed to reduce the above-mentioned potential sources of uncertainties.

3.8.2 Rock glacier kinematic time series

The project consortium elaborated kinematic time series on selected rock glaciers in the Swiss Alps, Norway, Svalbard, and Greenland based on SAR data acquired at a 6d- or 12d-intervall and with high spatial resolution. Typical lower and upper limits of detection for 6d-data are in the order 1 and 5 mm/d, respectively (equal to 0,4-2 m/yr). In addition, trends in rock glaciers velocity were computed in the Romanian Carpathians using ALOS-2 PALSAR-2 and Sentinel-1 SAR interferometry data. The results from this analysis are impressive and give good insight into the variability of rock glacier movement in time and space. The applied methodology promises a large step forward in monitoring of rock glacier movement at a global scale. One drawback of the time series analysis is that rock glaciers where only a single set of interferograms was used to define the velocity class are problematic in case they show strong variability in velocity throughout a year. However, it is also pointed out that continuous or seasonal monitoring has shown that observed rock glaciers develop a landform-specific but repetitive intra-annual behaviour. A solution for this problem might be to define a set of "typical" intra-annual behaviour classes and assign each monitored rock glacier (automatically?) to such a class. Such an approach implies the critical definition of different movement classes jointly by remote sensing experts and geomorphologists. The suggested approach might be promising as the project consortium studied already the full range of high to low overall velocities, large and small velocity variations, and increasing and stable interannual evolution of velocities in their rock glacier sample. Match up analyses showed that Sentinel-1 InSAR is slightly underestimating the velocities at GNSS locations possibly related to slope and resolution effects. This is also related to the limitation by the spatial resolution of the SAR data of about 15 m. Therefore, a representative point over the rock glacier (low internal variability) is necessary to select to calculate meaningful velocity time series. Furthermore, the rugged topography causes technical limitations of the InSAR technology thus the combination in the analysis with optical data and ground-based measurements is essential. These techniques are complementary and can hardly replace each other implying that also labour-intensive ground-based measurement must be kept ongoing or even extended for InSAR technology improvement. The project part about trends in rock glaciers velocity in Southern Carpathians focused on some rock glaciers in the Retezat Mountains. Severe problems in this study area were the slow and/ or hardly moving rock glaciers and missing appropriate ground-based measurement data. Longer time-series of GNSS-data for the Peleaga/Berbecilor and Judele rock glaciers in the Retezat Mountains are essential to improve the InSAR results. It is essential to keep InSAR and ground-based measurements ongoing in this patchy permafrost environment because the Retezat Mountains are an excellent site for marginal rock glacier activity representative for other mountain areas on Earth.

3.8.3 Mountain permafrost distribution model

A mountain permafrost distribution model was developed for an area in the Southern Carpathians. The precise extent of the model domain was not clear for me (possibly the area shown in Figure 4.2.1. in report D4.2). The permafrost model is based on the statistical relationships between BTS values and different predictor variables. The methodological description in the available documents is insufficient to clearly follow the chosen approach and would need at several places' clarifications. Furthermore, it is potentially misleading to use only a single year of BTS data for spatial permafrost modelling. This was shown by multi-annual BTS measurements in a comparable alpine setting in the Austrian Alps where substantial interannual variations of BTS-data were registered (Kellerer-Pirklbauer 2019). The same problem arises with short time-series of ground temperature data due to high interannual variability of the length or even presence/absence of the winter equilibrium temperature (Kellerer-Pirklbauer 2019). The accuracy of the used temperature sensors (+/-0.5°C) is a further source of uncertainty. Some prospects for future development for this objective are to extend the areal coverage of the BTS campaigns and carry our out multiple BTS campaigns at identical spots for several years. It is also recommended to extend the network of ground temperature sensors (currently only 8) to cover a wider range of topoclimatic settings in the Retezat Mountains. It is also a suggestion to change the data logger type to systems with a better accuracy to get more precise data. I am convinced that a more robust base source will certainly improve the model performance and will also help to quantify the uncertainty in the permafrost distribution model in the Romanian Carpathians.

4 PROGRESS IN REGARD TO USER REQUIREMENTS

4.1 Algorithm selection

The process of the algorithm selection as detailed in the URD [RD-21] and PVASR [RD-24] has been driven by the requirements of the research community, the regional permafrost modellers, remote sensing scientists, and field scientists working in mountain permafrost areas. The user community deemed the selected algorithms and standardization methodology as appropriate for their applications.

4.2 Product specification

In Tables 1 to 4 we specify the requirements from the URD [RD-21] and added a column to mark the respective status of achievement. The parameters for which the target requirements were met are highlighted in green and those for which the threshold requirements were met are highlighted in yellow. The parameters that are not fully meeting the requirements yet are highlighted in grey.

Table 1. *Summary of requirements for the Mountain Permafrost Distribution Model (MPDM) at regional scale in the Romanian Carpathians. The last column indicates the achievement status.*

	Threshold requirement	Target requirement	Status
	Coverage and sampling		
Geographical coverage Which region should the product cover?	Southern Carpathians	Retezat and Parâng Mountains	Southern Carpathians
Temporal extent	present	present	present
	Resolution		
Horizontal resolution	30 m	10 m	30 m
	Accuracy		
Accuracy	75%	90%	AUC = 0.83

Table 2. *Summary of requirements for trends in velocity of rock glaciers in the Romanian Carpathians. The last column indicates the achievement status.*

	Threshold requirement	Target requirement	Status
	Coverage and sampling		
Geographical coverage	Southern Carpathians	Southern Carpathians	Southern Carpathians
Temporal resolution	annual	monthly	30 days
Temporal extent	Last decade	Last decade	2014-2019
	Resolution		
Horizontal resolution	20 m	1 m	20 m
Vertical resolution/scale	20 m	1 m	<1m
Vertical extent	-	-	-
	Error/Uncertainty		
Accuracy	3 cm	6-7 mm	1 cm/year

Table 3. *Requirements for regional rock glacier inventories in mountain permafrost areas. The last column indicates the achievement status.*

	Threshold requirement	Target requirement	Status
	Coverage and sampling		
Geographical coverage and sampling [URq_01]	European Alps and Andes on the basis of mountain range whatever the national boundary	Global coverage on the basis of mountain range whatever the national boundary	Regions within European Alps and Andes, as well as several extra areas in Norway, Svalbard, Greenland, Tien Shan, Alaska and New Zeeland
Time frame and temporal extend [URq_02]	Current year	Assessed over 5-10 years and investigation in the past	Morphological attributed based on most recent data. Kinematics assessed based on Sentinel-1 dataset (past 5 years)
	Resolution		
Rock glacier identification [URq_03]	By a point	By its geomorphological footprint	By a point (optionally for some regions: geomorphological footprint)
Multi-unit differentiation [URq_04]	Different generations or different dynamics	Different dynamics, different generations and different connections to the upper slope	Different dynamics, different generations, and different connections to the upper slope
Update [URq_5]	10 years	10 years	TBD (iteration not yet applicable here)
	Attributes		
Rock glacier activity [URq_06]	-	Extended classification [RD-6]	Extended classification [RD-6]
Rock glacier destabilization [URq_07]	Optional	Useful	Added as useful attribute (optional)
Kinematics [URq_08]	Qualitative value (tbd)	Quantitative value (tbd)	Semi-quantitative attribute (following RD-24)
Moving areas [URq_09]	Optional. Classification (tbd)	Useful. Classification (tbd)	Classified velocity (following RD-24)
	Error/Uncertainty		
Precision & accuracy [URq_10]	-	Up to 30% of rock glaciers in an inventory could be undefined	Up to 30% of rock glaciers in an inventory could be undefined

Table 4. *Requirements for kinematic time series for selected rock glaciers in mountain permafrost areas. The last column indicates the achievement status.*

	Threshold requirement	Target requirement	Status
	Coverage and sampling		
Geographical coverage [URq_11]	European Alps	Global coverage	Selected examples in Switzerland, Norway, Greenland and Tien Shan
Geographical sampling [URq_12]	Sufficient rock glaciers representative in a defined regional context	At least 30% of representative rock glaciers in a defined regional context	Currently insufficient rock glacier number to be representative in a regional context
Update [URq_13]	5 years	1 year	TBD (iteration not yet

			applicable here)
	Resolution		
Time resolution [URq_14]	Yearly or seasonally with an annual time step	Yearly or seasonally with an annual time step	Level-1 time series with 6- or 12-days resolution within snow-free seasons
Temporal extent [URq_15]	Past 5-10 years	As far as possible back in time	All available Sentinel-1 series (5 years) and additional 60-70 years long in Tien Shan (optical)
Velocity value [URq_16]	Semi-quantitative value	Exact value	Exact value
Horizontal resolution [URq_17]	tbd	tbd	15 m for Sentinel-1 with 4x1 multilooking
	Accuracy		
Precision & accuracy [URq_18]	< 5 cm/yr	< 1 cm/yr	0.2-0.4 m/a for single Sentinel-1 interferograms

4.3 Integrated permafrost monitoring approach in the Romanian Carpathians

The current project proved the importance of an integrated monitoring approach for permafrost in the Romanian Carpathians. The results obtained in both permafrost modelling and RG dynamics showed that the results are best interpreted when using various data sources and measuring methodologies. Because of the patchy nature of the permafrost extent and because of the slow movement of rock glaciers, the results of the performed measurements are at the limit of what is practically possible to implement For example, the in-situ validation using DGPS for the RG dynamics were not relevant because the measured velocity was in the range of the instrumental error. In order to overcome this obstacle, the standard deviation of the measured displacement rates was used as a relative measurement of error and together with thermal and geophysical measurements it served as an indirect validation method.

Drawing from the findings, know-how and experience of the current project, the WUT has teamed up with UB (University of Bucharest) and UiO (University of Oslo) in order to develop a systematic monitoring network of permafrost in Romanian Carpathians. This will insure the continuation of RG dynamics, geophysical and GST measurements. Moreover, the initiative will try to set up two boreholes that will produce also ground temperature data at different depths, in accordance with GTN-P standards, starting from the summer of 2021. The data from the two boreholes will provide the needed information on active layer thickness and will improve the measured and model data on ground surface temperature.

There are ongoing discussions with the Romanian National Meteorological Administration (ANM), on how to integrate the data that will be collected with the temperature and precipitation data that they are providing for the Southern Carpathians.

The existing GST data collected from WUT, part of which was used in the current project, has been standardized and is planned to be analysed and published as a scientific paper that will present the findings of a decade of permafrost monitoring in the Romanian Carpathians. This will include data collected during the snow cover period of 2020 to 2021 thus, the planed paper will be submitted after the summer of 2021.

4.4 Potential for future work related to rock glacier inventories and kinematics

With reference to the requirements for regional rock glacier inventories (Table 3) and for kinematic time series for selected rock glaciers (Table 4) achieved within the current project, in the following we provide some explanations and indicate potential future activities.

4.4.1 Regional Kinematics-based Rock Glaciers Inventories

The requirements for regional rock glacier inventories in mountain permafrost area (Table 3) highlighted that users were interested by full mountain range coverage of the European Alps and Andes, and ideally by a global coverage. This is obviously a long-term work, practically impossible to realize in a few years. However, the work started within CCN2 goes into the good direction to fulfil the threshold requirement, by including in addition to case studies in the European Alps several other regions worldwide (Andes, Alaska, Greenland, Norway, Svalbard, Tien Shan and New Zealand). This paves the way towards a global coverage.

As further rock glacier kinematic inventories cannot be compiled globally within short time, a selection of priority regions should be driven by user requirements but also by objective scientific criteria, which can for instance be derived from the Permafrost_cci global permafrost modelling. Related criteria could include for instance to cover a wide range of climatic and permafrost types, topographic settings, or local relevance (e.g. natural hazards, water resources).

Based on the kinematic inventories a first set of derived parameters could be demonstrated, such as estimation of periglacial sediment fluxes and comparison over different mountain ranges. The rock glacier geographic and kinematic attributes could be put into relation with the Permafrost_cci permafrost model in order to characterise the setting of the rock glaciers, but also to improve the permafrost model over mountain regions.

All inventories follow the minimal requirement of a point-based identifiers. In addition, some of the inventories already include indicative polygon-based outlines. Practical guidelines defining clear rules in this matter are however still ongoing by the IPA Action Group "Rock glacier inventories and kinematics".

Because the requirement for the update of the inventories is on the order of 5 to 10 years, further iterations are not applicable within a short-term project.

4.4.2 Rock glacier kinematic time series (RGK)

The standardization of rock glacier kinematic time series (RGK) is meant to follow the guidelines defined by the IPA Action Group "Rock glacier inventories and kinematics", in agreement with the proposal for the next GCOS Implementation Plan, with the objective to exploit RGK as an associated parameter of ECV Permafrost. This effort is still ongoing and therefore several user requirements could not yet met for this product (see Table 4).

The results processed so far with InSAR, SAR offset tracking and matching of optical images for selected rock glaciers in Switzerland, Norway, Greenland and Tien Shan can be however already considered to discuss some of the current advantages and limitations related to the generation and accuracy estimation of RGK time series and to refine the processing chains.

InSAR-derived seasonal rock glacier speed time series offer a new perspective for monitoring and understanding rock glacier response to climate change. Respective measurements should be expanded in the future. For this purpose, a sound scientific strategy should provide priorities for which rock glaciers should be monitored. Similar to the inventories, such prioritization should consider user requirements (e.g. ground investigations) but also cover a range of geographic, climatic, topographic, or applied criteria. Selection of prioritization criteria, selection of actual monitoring rock glaciers, and conduction of actual measurements combines the goal to the design and population of a first-order worldwide satellite-based network of seasonal rock glacier speed variations.

InSAR measurements should then be complemented by photogrammetric measurements to provide long-term average reference speeds. So far, photogrammetric measurements were only possible from high-resolution aerial or satellite data. Though, Sentinel-2 observation series grow to be long enough to also derive surface velocities for selected fast rock glaciers. This work requires high-precision image matching methods, possibly based on entire stacks of Sentinel-2 data, not only pairs. Such methods could be implemented in future climate change observation initiatives, and complement above observation network of rock glacier kinematics.

When the above-mentioned technical elements are improved, a larger number of rock glaciers can be processed. This will provide a sufficient geographical sampling, necessary to represent a defined regional context and be able to express regional climatic indexes.

5 PUBLICATIONS AND OUTREACH

5.1 Publications

Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Darrow, M., Delaloye, R., Lambiel, C., Rouyet, L., Ruiz, L., Strozzi, T., A complementary kinematic approach to inventory rock glaciers on a global scale, in prep.

Kääb, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M., & Kokarev, A., 2020: Inventory, motion and acceleration of rock glaciers in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s. The Cryosphere, 15, 927–949, 2021, doi:10.5194/tc-15-927-2021.

Retelle, M., Christiansen, H., Hodson, A., Nikulina, A., Osuch, M., Poleshuk, K., Romashova, K., Roof, S., Rouyet, L., Strand, S.M. and Vasilevich, I. 2020: Environmental Monitoring in the Kapp Linne-Gronfjorden Region (KLEO), In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 85–107. Available on: https://sios-svalbard.org/sites/sios-svalbard.org/files/common/SESS_2019_03_KLEO.pdf.

L. Rouyet, T. R. Lauknes, H. H. Christiansen, S. M. Strand and Y. Larsen, 2019: Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR, Remote Sensing of Environment, Volume 231, 111236, https://doi.org/10.1016/j.rse.2019.111236.

Rouyet, L., Lilleøren, K., Böhme M., Vick, L., Delaloye, R., Etzelmüller, B., Larsen, Y., Lauknes, T. R., , Blikra, L. H., Regional InSAR inventory of slope movement in Northern Norway, Submitted to Frontiers in Earth Science.

Strozzi, T., Caduff, R., Jones, N., Barboux, C., Delaloye, R., Bodin, X., Kääb, A., Mätzler, E. and Schrott, L, 2020: Monitoring Rock Glacier Kinematics with Satellite Synthetic Aperture Radar. Remote Sensing, 12(3), 559, doi:10.3390/rs12030559.

5.2 Presentations and posters

C. Barboux, C. Lambiel, T. Strozzi and R. Delaloye, Regional trend of rock glacier kinematics derived from DInSAR data, Southern Hemisphere Regional Conference on Permafrost (SouthCOP), Queenstown (New Zealand), 4-14 December 2019.

C. Lambiel, T. Strozzi, N. Paillex, S. Vivero and N. Jones, Mapping rock glaciers in the Southern Alps of New Zealand with Sentinel-1 InSAR, Southern Hemisphere Regional Conference on Permafrost (SouthCOP), Queenstown (New Zealand), 4-14 December 2019.

Lauknes, T.R., Rouyet, L., Larsen, Y., Grahn, J., Böhme, M., Dehls, J. 2019. Multi-geometry Sentinel-1 InSAR for Characterizing Ground Deformation in Norway. Oral presentation. AGU Fall Meeting, 9–13 December 2019, San Francisco, U.S.A.

Rouyet, L., Liu, L., Lauknes, T.R., Christiansen, H.H., Strand, S.M., Larsen, Y., Stendardi, L., Karlsen, Johansen, Malnes. 2019. Seasonal dynamics of permafrost landscapes: InSAR ground

displacements and controlling factors documented by in situ and Sentinel-1/-2 remote sensing data. Oral presentation. AGU Fall Meeting, 9–13 December 2019, San Francisco, U.S.A.

Rouyet, L., Liu, L., Lauknes, T.R., Christiansen, H.H., Strand, S.M., Larsen, Y. 2020. Mapping the timing of seasonal thaw subsidence and frost heave in central western Spitsbergen using InSAR. SIOS online conference on Earth Observation, Remote Sensing and Geoinformation applications in Svalbard. Oral presentation. 04-05 June 2020.

F. Sirbu, A. Onaca, F. Ardelean, B. Magori and P. Urdea, Present state of marginal mountain permafrost in South Eastern Europe, EGU General Assembly 2020, https://doi.org/10.5194/egusphere-egu2020-20066.

T. Strozzi, U. Wegmüller, R. Caduff, R. Delaloye and C. Barboux, Monitoring Rock Glacier Kinematics with Sentinel-1 SAR Interferometry, 2019 Living Planet Symposium, 13-17 May 2019, Milan, Italy.

T. Strozzi, A. Bartsch, S. Westermann, J. Obu, G. Grosse, B. Heim, A. Wiesmann, C. Kroisleitner, K. Aalstad, J. Fiddes, A. Kääb, H. Matthes, I. Nitze, A. Rinke, M. Wieczorek, G. Hugelius, J. Palmtag, C. Barboux, C. Pellet, A. Bertone, R. Delaloye and F.M. Seifert, Space-borne studies of permafrost in the Arctic within ESA's CCI, 2020 European Polar Science Week, Virtual Event.

5.3 News stories

A project summary has been published as part of the IPA annual bulletin 'frozen ground' #43 (2019).

5.4 Outreach activities

The CCI permafrost project has been also presented at the ALPSMOTION (Investigating alpine permafrost dynamics from space to the field) summer school at EURAC, Bozen, on 16th of July 2019.

A poster of the project was presented at the 9th CCI Co-location Meeting (online).

5.5 Student teaching and courses

Outcomes from CCN CCI projects were exploited for student teaching and courses:

May 2019: Rouyet 1-day guest lecturer in remote sensing of permafrost, course AG-330/830 "Permafrost and Periglacial Environments", The University Centre in Svalbard (UNIS).

August 2019: Rouyet 1-day guest lecturer in remote sensing for geohazards assessment and monitoring, course GEO-3135, The Arctic University of Norway in Tromsø (UiT).

December 2018-2020: GG.0451, Rouyet guest to Seminar in Geomorphology, University of Fribourg. "Investigation of ground dynamics on rockslides and permafrost landforms using radar interferometry".

6 REFERENCES

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Brardinoni F., Scotti R., Sailer R., Mair V., 2019: Evaluating sources of uncertainty and variability in rock glacier inventories. Earth Surface Processes and Landforms, 44/12, 2450-2466. https://doi.org/10.1002/esp.4674.

Delaloye, R., Staub., B., 2016. Seasonal variations of rock glacier creep: time series observations from the Western Swiss Alps. In: Günther, F. and Morgenstern, A. (Eds.) (2016): XI. International Conference on Permafrost – Book of Abstracts, 20 – 24 June 2016, Potsdam, Germany. Bibliothek Wissenschaftspark Albert Einstein. 22-23.

Jones, D.B., Jones, Harrison, S., Anderson, K., Betts, R.A., 2018. Mountain rock glaciers contain globally significant water stores. Sci. Rep., 8 (1), 2834.

Kellerer-Pirklbauer A., 2019: Long-term monitoring of sporadic permafrost at the eastern margin of the European Alps (Hochreichart, Seckauer Tauern range, Austria). Permafrost and Periglacial Processes, 30/4, 260–277. https://doi:10.1002/ppp.2021.

Necsoiu, M., Onaca, A., Wigginton, S., Urdea, P., 2016, Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery, Remote Sensing of Environment, 177, 21–36.

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Popescu, R., Vespremeanu-Stroe, A., Onaca, A., Cruceru, N., 2015. Permafrost in the granitic massifs of Southern Carpathians (Parâng Mountains). Zeitschrift für Geomorphologie, 59, 1, 1-20.

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5.2 Acronyms

AD	Applicable Document
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
B.GEOS	b.geos GmbH
BTS	Bottom Temperature of Snow Cover
CCI	Climate Change Initiative
CCN	Contract Change Notice
CR	Cardinal Requirement (as defined in [AD-1])
DARD	Data Access Requirement Document
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
ESA DUE	ESA Data User Element
E3UB	End-to-End ECV Uncertainty Budget
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
GTOS	Global Terrestrial Observing System
GUIO	Department of Geosciences University of Oslo
INSAR	Synthetic Aperture Radar Interferometry
IP	Implementation Plan
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
LST	Land Surface Temperature
MPDM	Mountain Permafrost Distribution Model
NORCE	Norwegian Research Centre AS
PE	Permafrost Extent
PS	Processing System
PSD	Product Specifications Document
PVASR	Product Validation and Algorithm Selection Report
PUG	Product User Guide

PVP	Product Validation Plan
QA4EO	Quality assurance framework for earth observation
RF	Random Forest
RD	Reference Document
RG	Rock Glacier
RGI	Rock Glacier Inventories
RGK	Rock Glacier Kinematics
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SWE	Snow Water Equivalent
T	Temperature
UNIFR	Department of Geosciences University of Fribourg
UNIS	University Centre in Svalbard
URD	Users Requirement Document
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WUT	West University of Timisoara